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CIRCUMSTELLAR DISKS: FUELING STARS AND FORMING PLANETS

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ABSTRACT

The coming decade promises to see the most progression to date in understanding the formation and early evolution of extrasolar planetary systems. The first five years will see the culmination of more than a decade's work to get planned surveys in the far-infrared and submillimetre on the sky through the Herschel Space Observatory and the James Clerk Maxwell Telescope. Most importantly, the completion of ALMA construction in 2013 will provide the critical instrumentation to resolve and understand the dynamics, chemistry and evolution of circumstellar disks in star forming regions and the substructure of debris disks around main sequence stars, counterparts to our own outer solar system and Kuiper Belt. To make the most effective use of the opportunities for advancing disk studies in the coming decade, Canada must foster a vigorous, well populated community of researchers to take advantage of our (essentially) unlimited access to ALMA and EVLA; complete the JCMT Legacy Survey, critical for the detection of disk hosts which will be the ALMA and EVLA targets; work to provide the means to build research teams across Canada, including at NRC; encourage computing consortia to meet the challenge of disk theory and modeling simulations; and pursue Band 1 development for ALMA.

Subject headings:

1. ABOUT CIRCUMSTELLAR DISKS

Circumstellar disks are the dusty and gaseous structures from which stars and planetary systems form. They are flat and thin, with outer radii up to several hundred AU in extent. As stars form, mass from surrounding clouds flows through disks and is funneled onto forming stars (Figure 1). By some yet-undefined process, inhomogeneities arise in the disks that can lead to the formation of planets (Figure 2). The physical conditions of disks are therefore of great interest to those studying protostellar evolution or planet formation. On astronomical scales, however, such disks are tiny, making them difficult to resolve. The highest observational resolutions possible are needed to investigate their physical natures, i.e., their mass, density, temperature, velocity (turbulence), magnetic fields and chemical abundance distributions. Disks are typically detected due to excess infrared or submm/mm emission from a young stellar object or main sequence star.

There are four broad classifications of circumstellar disk: protostellar, protoplanetary, transition and debris. Protostellar disks are accretion disks that form at the earliest phase of star formation and persist until the star reaches the main sequence. It is through these disks that some fraction of the material from the low-density envelope which surrounds the disk reaches the forming star. The rest is lost to stellar winds and outflow driven by the disk (Figure 3). Disks around forming stars are also gas-rich. As such, the physical conditions within disks can be probed by multi-wavelength observations in molecular lines (Figure 4) while continuum observations provide information in the dust component. Models of accretion disks predict various geometries (e.g., flared) with wide ranges of temperatures and densities, due in part due to distance from the forming star, but also due to self-shielding layers which insulate the cold disk midplane. As disks evolve to be 'protoplanetary', solids are thought to "settle" to the disk midplane, where agglomeration of dust grains must occur to produce larger planetesimals, the seeds of planets.

Transition disks were detected only in the last decade by the Spitzer Space Telescope and are exemplified by a loss of flux (and material) from the inner disk outward, forming a hole associated with the presence of forming planets (Figure 5). How extended or massive disks appear depends strongly on the wavelength observed since outer disks, which are colder, can be present even after warm disk components disappear. Therefore, planets can still be forming in outer disks even as inner disks dissipate (Figures 6 & 7).

Debris, or secondary, disks are formed from large "planetesimals" left behind after the dissipation of the protoplanetary disk. Around main sequence stars of any age, asteroids or comets in orbit around the star can undergo collisions. Such collisions between these larger planetesimals create a collisional cascade, from which solids of smaller and smaller size are created. When micron- to mm-sized grains are once again present, the debris disk is again observable from the optical to centimetre wavelengths. Debris disks require ongoing collisions of the large parent population of planetesimals to sustain them. Our own solar system has two major components to its debris disk: the asteroid belt and the Kuiper-Edgeworth belt. Compared to gas-rich accretion disks, debris disks are very optically thin, faint and spatially extended. The observable mass in dust is typically less than a lunar mass.

During the past decade, SCUBA on the JCMT has made the most significant contributions to our understanding of debris disk structure (Figure 8). Among them, SCUBA detected and resolved the nearest and oldest known debris disks, Epsilon Eridani and τ Ceti (Figure 8) and detected the first debris disk around an M star, AU Mic (Liu, Matthews, Kalas & Williams 2004) which led to vigorous followup with HST and other facilities (Figure 9).

2. PROBING THE FORMATION AND EVOLUTION OF PLANETS

Forming planets must acquire their mass before their natal protoplanetary disks dissipate. Thus, the formation and early evolution of planets is deeply connected to the physical conditions within disks (e.g., the density profile, temperature, etc.). Observations of disks in regions of star formation show that disk lifetimes lie in the range of $3 - 10$ Myr. This places interesting constraints on planet formation mechanisms. The timescales of core accretion models are a few tens of Myr for terrestrial planets, while the process leading to the formation giant planet cores remains uncertain. Recent calculations that include the migration of planets can speed up this process (e.g., Matsumura et al.) but still require a couple of Myr to do the job. Gravitational instability models in which the planets collapse within the disk could form giant planets in orbital timescales ($t \ll 1$ Myr), though some models require conditions that could only be met in the outer disk, a conclusion drawn largely within Canada (Matzner & Levin 2005), or higher disk masses than typically observed. The current understanding of giant planets on wide orbits around A stars is largely thanks to Canadian efforts (see Kratter et al. 2010). Gravitational fragmentation into planetary or stellar mass companions is in fact predicted for stars only marginally more massive than the Sun (Figure 10).

Identifying *where* and *when* dust coagulation occurs in disks are critical to constrain current models of planetary formation. Growth from submicron- to micron-sized particles can be traced with infrared spectroscopy and imaging polarimetry. The next step, growth beyond micron sizes, is readily studied by determining the slope of the spectral energy distribution (SED) of the dust thermal emission at sub-mm, mm and cm wavelengths.

In both protoplanetary and debris disks, models show that the presence of planets can open up gaps in their host disk or create sharp inner or outer edges to the disk (Figure 11). In debris disks, the dynamical effects of the planet can create resonances which trap dust material; the detection of these resonance patterns has been used to infer the presence of planets (e.g., epsilon Eridani, Vega). These gaps will be detectable to ALMA's resolution of better than 0.01 arcseconds.

The resolved images of disks will do more than just identify potential locations of giant planets. The measured thermal and density structure will constrain models of migration timescales for planets in disks as well as the direction of torque experienced by a planet in a disk of given surface density and temperature. These models generally adopt a simple power-law radial density profile for the disks, resulting in migration timescales that are short by two orders of magnitude compared to the disk lifetime. If ALMA observations of disks suggest more complex radial profiles, then the current picture of rapid planet migration would have to be revised.

Theories also have already predicted potential locations for the build up of planetesimals. For example, regions of low turbulence are predicted in regions of high density within disks. These regions, called "dead zones" have been predicted to be foci for the assembly of planetesimals at the inner and outer edges of the disks. Calculations predict that such a dead zone would initially extend over 10 AU in disks and then shrink as the disk material accretes onto the star. The presence, size and variation with disk age of a region of high density and low turbulence can be measured directly with molecular spectroscopy in disks with ALMA.

Coupled observations of disk properties, dust content, inhomogeneities in disk structure such as snow lines and dead zones, and chemical composition will be also be needed to constrain models of extrasolar planet structure.

The process of collapse of the natal envelope of giant planet atmospheres determines the underlying structure of the giant planet, from the core to the outer atmosphere. Modelling of these processes and their impact on the planetary structure is the end goal of many of the observational campaigns and requires substantial investment in theoretical work. Such modelling may even lead to understanding of the processes the drives the excess heat capacity of Jupiter and its chemical peculiarity. The field of Jovian modeling is yet to be developed in Canada, and we desperately need to build capacity here if we are to take advantage of the investments being made in high-contrast imaging and sub-mm interferometry which will lead to many detections of potential planetary mass bodies in formation (e.g., HL Tau, Figure 12).

3. 2010-2020: A GOLDEN AGE OF DISK STUDIES

Canadian involvement in Spitzer, Herschel and JCMT surveys of nearby star-forming regions have well positioned our community to capitalize on ALMA's potential for studies of protoplanetary disks. The combination of these surveys will detect scores of disk hosts which will be the targets for ALMA. In addition, Canadian leadership of the deepest statistical surveys for debris disks around nearby stars with the Herschel Space Observatory (the only Open Time Key Program led by a Canadian, just underway and already yielding exciting science, see Figure 13) and the JCMT provides our community with a unique opportunity to expand into the area of debris disk research which has not been well represented in Canada until now. Both these surveys are statistical in nature, reaching depths never before reached in disk mass. They will measure the incidence of, and characterize, debris disks across a range of spectral types and ascertain where our own Solar System fits in the continuum of disk properties. Resolved debris disk images will also provide a means of detecting planets undetectable by other means (large period, low mass), leading to a natural complementarity with standard exoplanet detection techniques.

ALMA and the EVLA will supercede all other facilities for the study of protoplanetary disks, moving their study from a case-by-case approach to one truly statistical in nature. This will enable us, for the first time, to study the history of disks through their evolution from the youngest protostellar phases, through transition disks to the dust-dominated debris systems wherein the final steps to terrestrial planets with the retinue of minor bodies dominate. Among the three top level science goals of ALMA is the ability to detect and image gas kinematics in protoplanetary disks undergoing planetary formation at 150 pc. It will also detect many complex, organic molecules toward disks. At ALMA's observing wavelengths, its capability for imaging the continuum dust emission in these disks is also second-to-none. *The unique properties of the interferometers will allow, for hundreds of disks, disk emission to be measured distinctly from the surrounding envelope and cloud material, by tuning observations to the correct spatial scales.* Several key areas of research will make huge strides due to these new capabilities.

- ALMA will measure substructure within disks with unprecedented resolution in the submm/mm, better than 0.01 arcseconds, corresponding to a resolution of 0.03 AU, 0.5 AU and 1.2 AU at the distances of the nearest debris disk, nearest protoplanetary disk and nearest large star-forming regions, respectively.
- The direct observation of the variation of temperature, density, mass, turbulence, magnetic fields, degree of ionization and dust grain properties as a function of radius and disk height will be measurable, enabling the testing of (in some cases, long-standing) theories of disk formation, chemical models, evolution, mass loss to the central star, launching of outflows and winds,

dead zones, dust settling and planet formation. For example, ALMA may finally resolve the origin of outflows, in particular, whether or not they originate on extended regions of the disk. This would help to answer a key question that has been in the literature *for nearly 30 years*.

- ALMA and the EVLA could reveal discrete concentrations of large grains within disks which could be planets in formation, as has been done for HL Tau (Figure 12). Development of Band 1 will greatly enhance ALMA's capability in this area. In addition to compact dust clumps in disks, other structures in disks such as inner gaps, holes and other substructures will reveal potential planets in disks.
- The search for disks around massive forming stars, a hot topic of research, will move forward at last, allowing observations to catch up to theory (see Figure 14). The large distances and high degree of clustering of high mass star-forming regions make interferometers essential to even discriminate sources.

ALMA and the EVLA will make significant contributions to debris disk research, but the spatial extension and low surface brightness of debris disks makes their interferometric observations more challenging than protoplanetary disks. ALMA and EVLA will target specific debris disks rather than survey hundreds of disks.

GPI, the Gemini Planet Imager, will be commissioned in 2011 on Gemini South. The main purpose of GPI is of course the detection of extrasolar planets around main sequence stars, and systems detected to have debris disks in the Herschel and JCMT surveys will be natural targets for GPI to look for planetary mass companions close to the star. GPI's additional polarimetric capability will be excellent for imaging warm components of disks in scattered light.

The James Webb Space Telescope, JWST, has a planned launch in 2014. In the near-IR and mid-IR, emission from circumstellar disks can be very strong since it arises from the warmest dust very near the star. When this emission is missing, it is strong evidence that a gap or hole is present in the inner part of the disk. As done already by ISO and Spitzer (with considerably less sensitivity and resolution – JWST will resolve disks), the near-IR and mid-IR also allows the study of dust composition which reveal grain growth, crystallization and chemical processing (e.g., of PAHs). PAHs and dust have a large influence on the physical structure of the disk and the disk chemistry. Grain growth is of course also the first step towards planet formation. The tunable filter imager on JWST will be particularly effective at searching for planets within debris disks host systems with evidence for central holes identified through the Herschel and JCMT surveys or JWST mid-IR images. While it continues to function, STIS on HST will continue to provide a means of obtaining resolved images of debris disks in scattered light. Finally, SOFIA, the Stratospheric Observatory for Far-Infrared Astronomy, will provide narrow-band images and spectroscopy in the wavelength range 30-60 μm which is not available from other instruments.

4. WHAT WE NEED TO SUCCEED

Realizing the goals for the coming decade, which promises to be the most vigorous yet in the area of circumstellar disk research, will require:

- a vigorous, distributed community able to take advantage of ALMA and EVLA. Canadians have (essentially) unlimited access to both, and both will be excellent for disk research.
- better integration of related research areas of star and planet formation and exoplanet science with disk research. This will maximize scientific output from all the premiere facilities available in the coming decade to achieve the goal of understanding the coupling of disk and planet evolution.
- completion of the JCMT Legacy Survey. This is essential to keep Canadian researchers involved, and in leading roles, in the detection of the scores of potential disk hosts which will be identified by the JLS. Disks targeted by ALMA will be drawn from the wide-field surveys of single-dish facilities.
- the means for ALL Canadian researchers to have access to the manpower they need to build research teams. The means to hire more postdoctoral researchers in observational science, and star formation particularly, is essential. The difficulties in circumstellar disk research is compounded by the concentration of observational disk expertise at NRC/HIA.
- strong support for major computing consortia. Modeling of disk and planet evolution soak up many 10^5 cpu hours just to do one major model that has basic physics of collapse, outflow, radiative transfer, and dust evolution, and all of this can only cover a fraction of the disk's lifetime. The challenge is to follow such simulations of protoplanetary disks which include 3D effects, radiative transfer, and chemistry over a million years of disk evolution (rather than the current few hundred orbits). Advances in software, parallel computering, and hardware are having a significant impact on this field (e.g., SHARC-NET, but we need to build its success). Good models of disks that can accurately predict that snow lines (points of ice sublimation) or dead zones will allow much more comprehensive theories of planet formation to be constructed.
- Band 1 development and implementation for ALMA. ALMA's operations plan includes future development projects. Canada has already shown interest in building Band 1 receivers for ALMA. These, the lowest wavelength band of ALMA (31.5-45 GHz, 1cm) would greatly augment ALMA's capability in disk research. With Band 1 receivers, ALMA would be sensitive to emission from dust grains as large as cm-sized pebbles, a likely reservoir of significant mass in both protoplanetary and debris disks. Evidence for small pebbles has been detected in several disks, including TW Hya, the closest protoplanetary disk to the Sun (50 pc).

5. THE FAR FUTURE

In the long term, once the facilities of the coming decade have come online and are impacting disk and planet evolution research, we can look forward to the next generation of facilities. The planet imager and mid-IR camera on TMT will continue to impact planet and disk studies. For debris disk research, sensitive, high resolution single dish facilities like CCAT will represent the next step in resolved imaging for statistical samples of debris disks. The SKA, if its planned high frequency component is retained, will enable imaging of grain growth and forming planet condensations within 1 AU of nearby stars. Finally, proposals for a far-infrared interferometer in space will succeed ALMA in disk imaging and resolution within habitable zones where terrestrial planets form.

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FIG. 1.— Artist's rendition of a protoplanetary disk in the optical/NIR. The disk extincts the light of the forming central protostar, which escapes only along the poles. The disk itself is embedded in an envelope of gas and dust which feeds the thin, accreting disk.

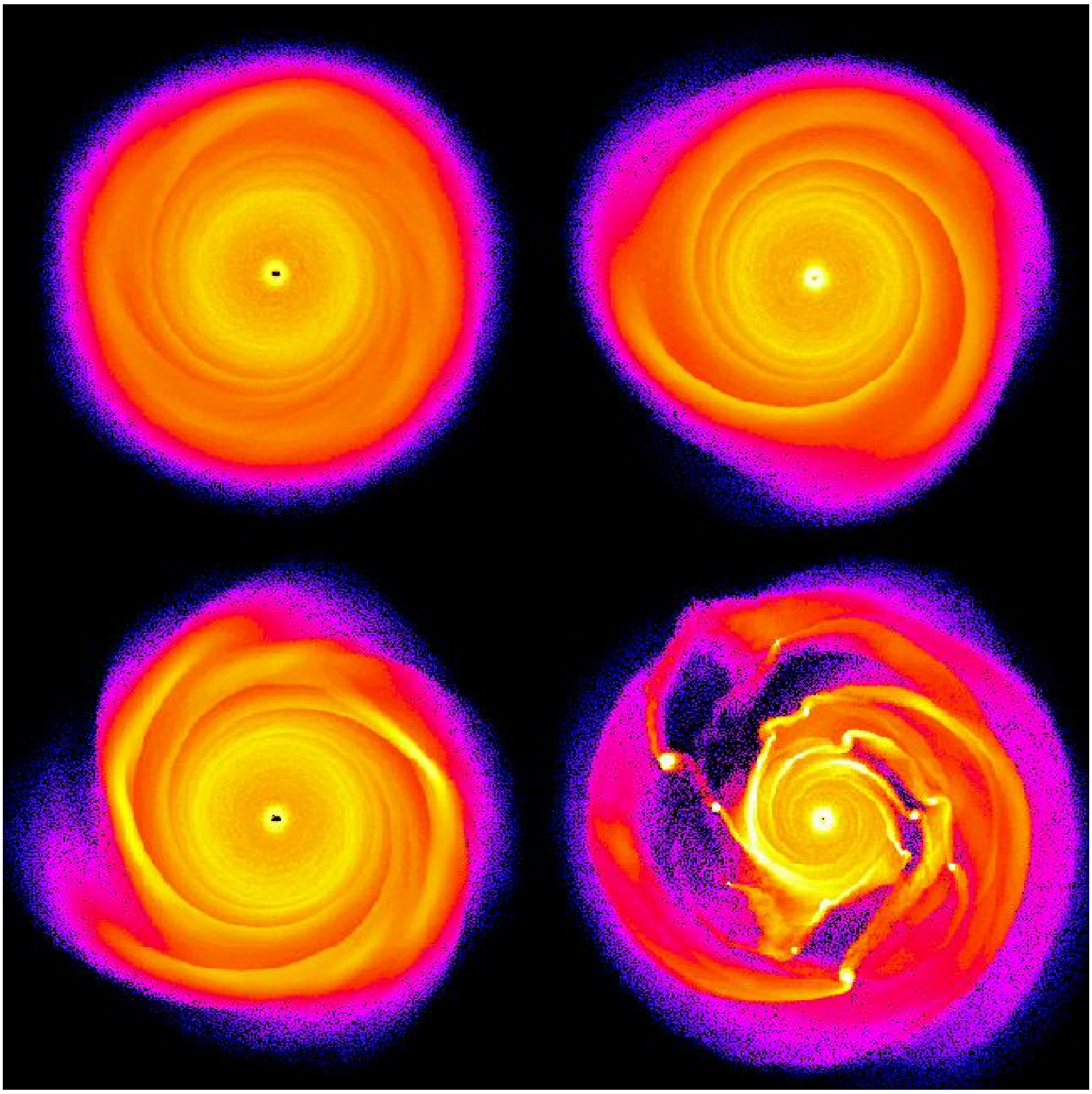

FIG. 2.— Four panels show the evolution of a disk of gas around a young star. In the top two panels the disk is not cold or heavy enough to fragment [Q=1.75]. In the lower two panels the disk is marginally unstable to fragmentation [Q=1.4]. The left two panels are after 160 yr and the right two after 350 yr. The formed planets have properties similar to the observed large extrasolar planets. (Shen, Wadsley, Hayfield & Ellens, 2010)

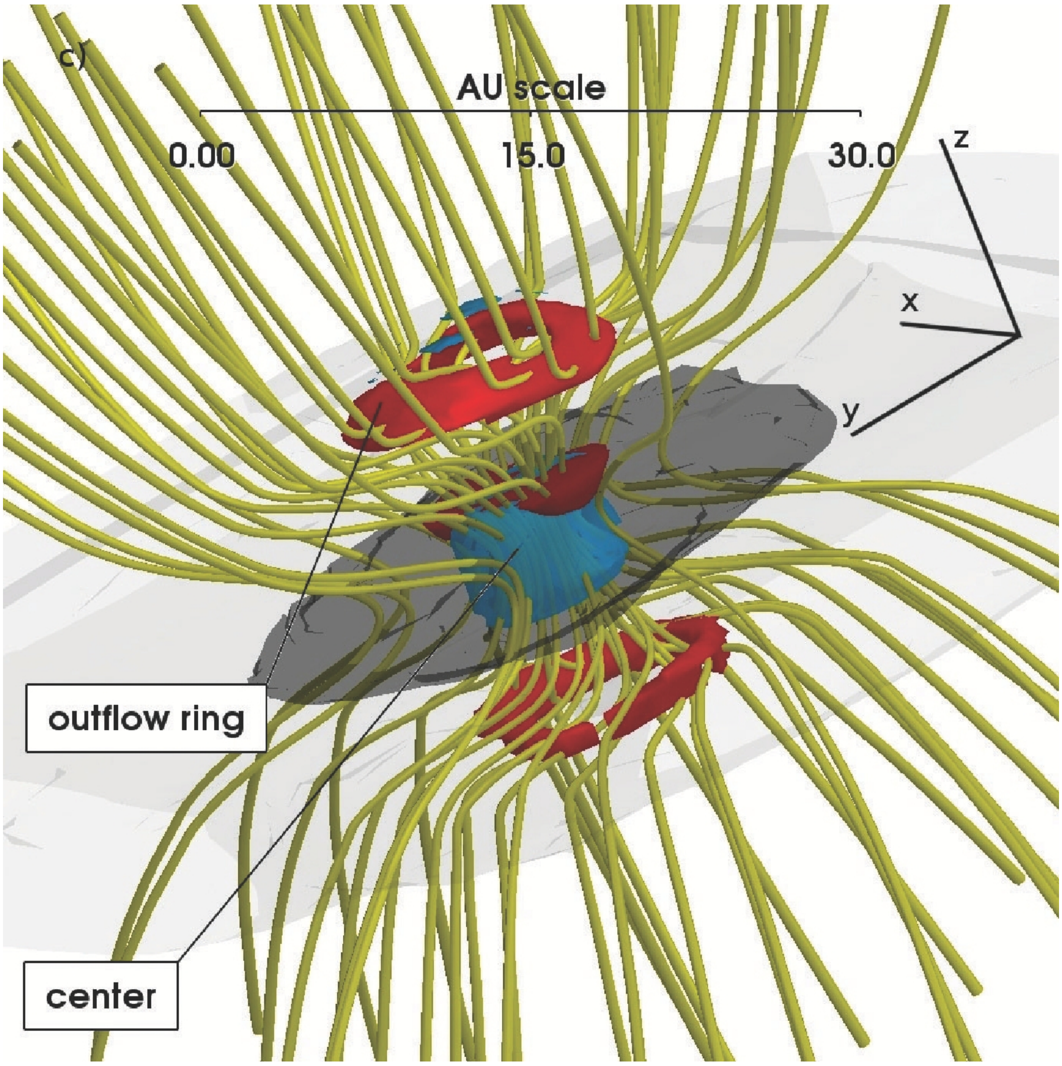

FIG. 3.— This model shows the inner disk that forms in a collapsing, rotating, and magnetized Bonner-Ebert, unstable sphere that has 10% density perturbation applied. The disk has a column density of 4.2×10^3 g cm^{-2}. The black and gray surfaces show two different densities at $n = 2.6 \times 10^11$ cm^{-3} and 2.6×10^{10} cm^{-3} respectively. The temperature contours at 85 K are shown in blue. Outflow velocity contours are shown in red, and are 0.3 km s^{-1} at this early stage. The magnetic field lines are shown as yellow tubes. (Duffin & Pudritz 2009)

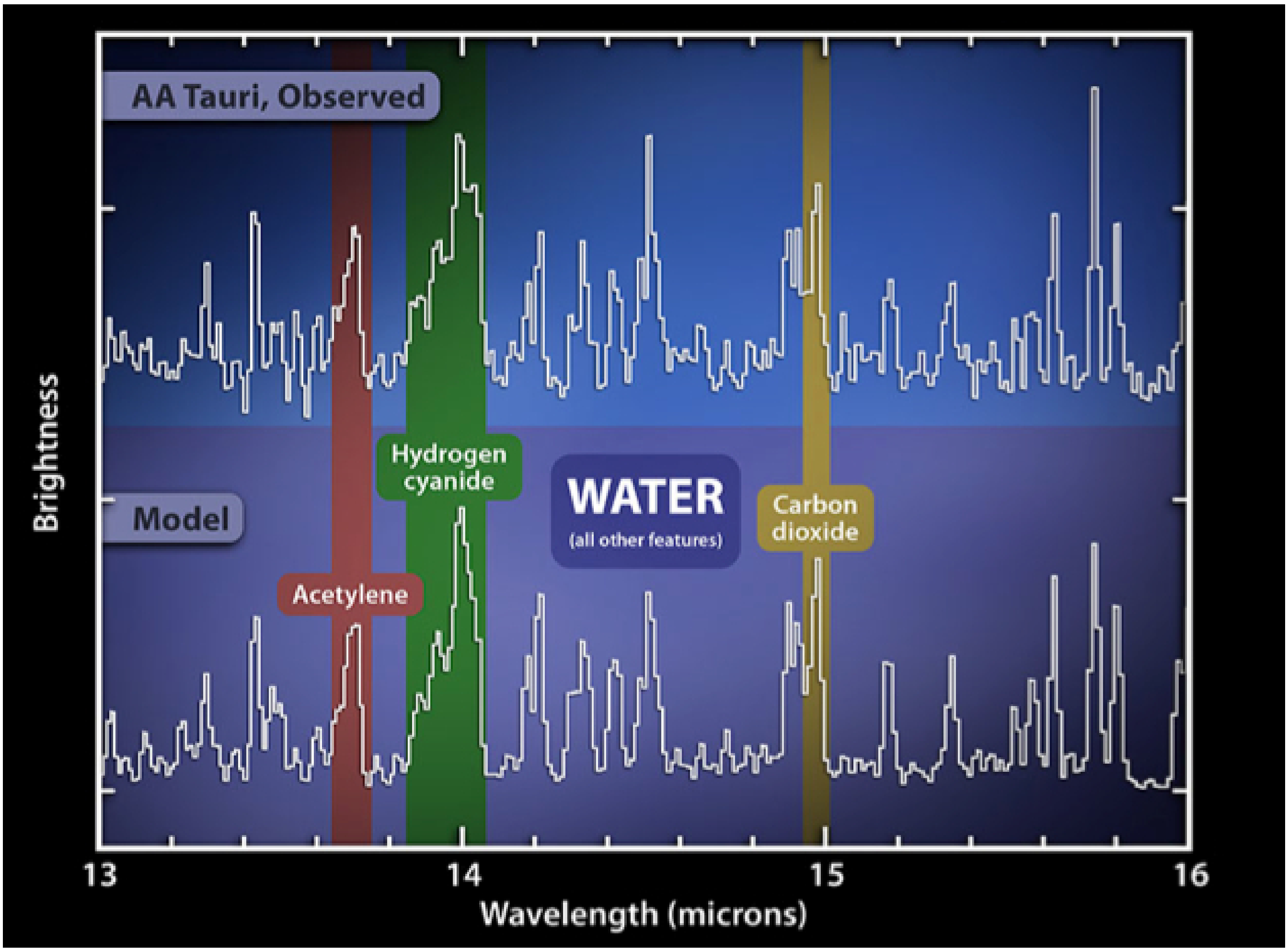

FIG. 4.— Spitzer IRS data, and model predictions, for the detections of hot water and organics in the AA Tauri protoplanetary disk. Such features in the inner parts of protoplanetary disks are common. (Carr & Najita 2008)

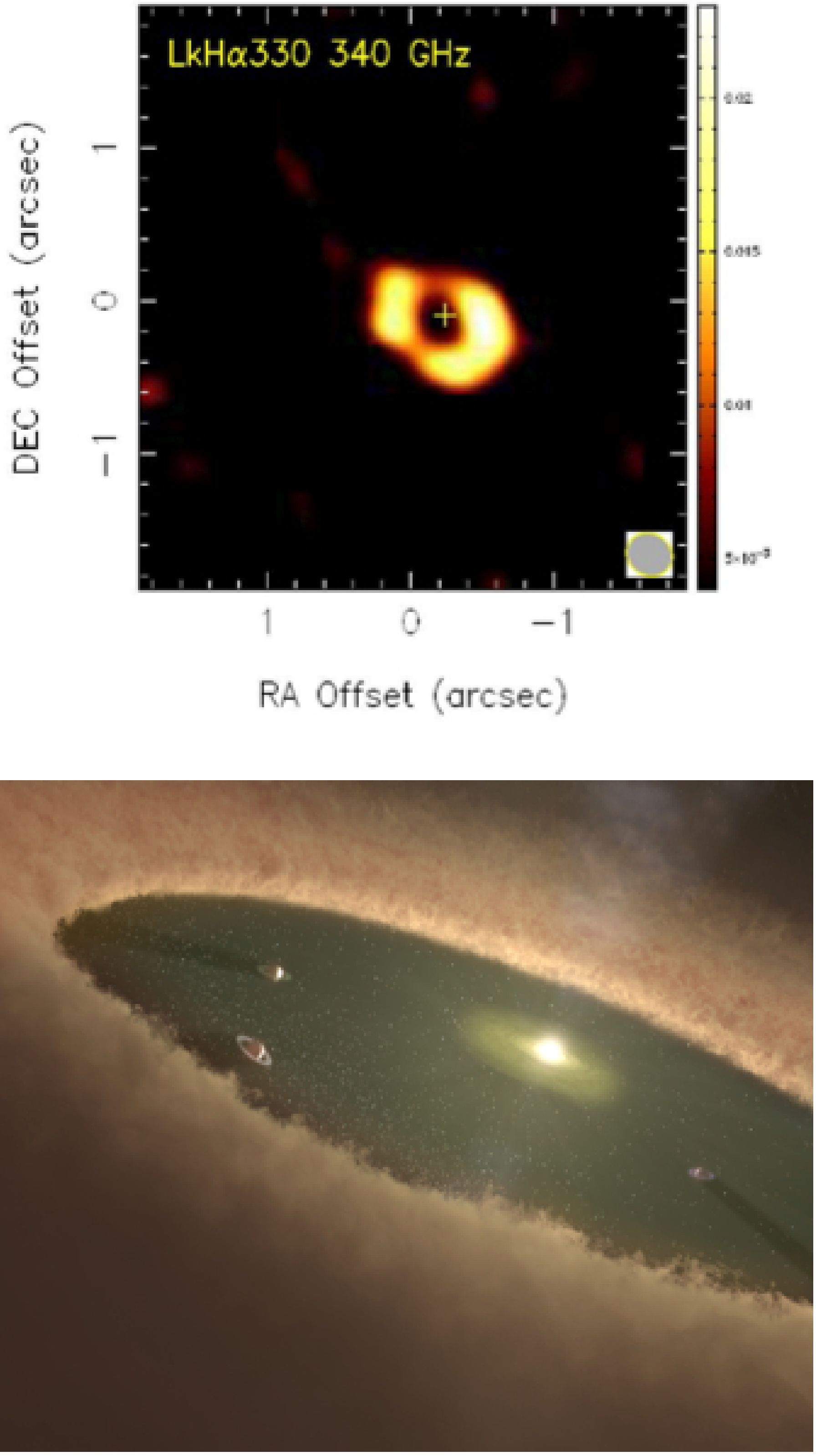

FIG. 5.— *Top:*Submillimeter Array imaging of a 40 AU radius inner gap in the disk around LkHα 330 using 880 μm dust continuum imaging. This large gap is fully resolved by the SMA observations and mostly empty of dust with less than $1.3\times10^{-6}M_{\odot}$ of solid particles. Gas (as traced by accretion markers and CO M-band emission) is still present in the inner disk. The good agreement of the spatially resolved data and a spectrophotometry-based model (right) supports interpretation of dust emission deficits in SEDs as evidence of inner gaps and holes. (Brown et al. 2008) *Bottom* Artists rendition of a transition disk with planets already formed in the cleared out disk interior.

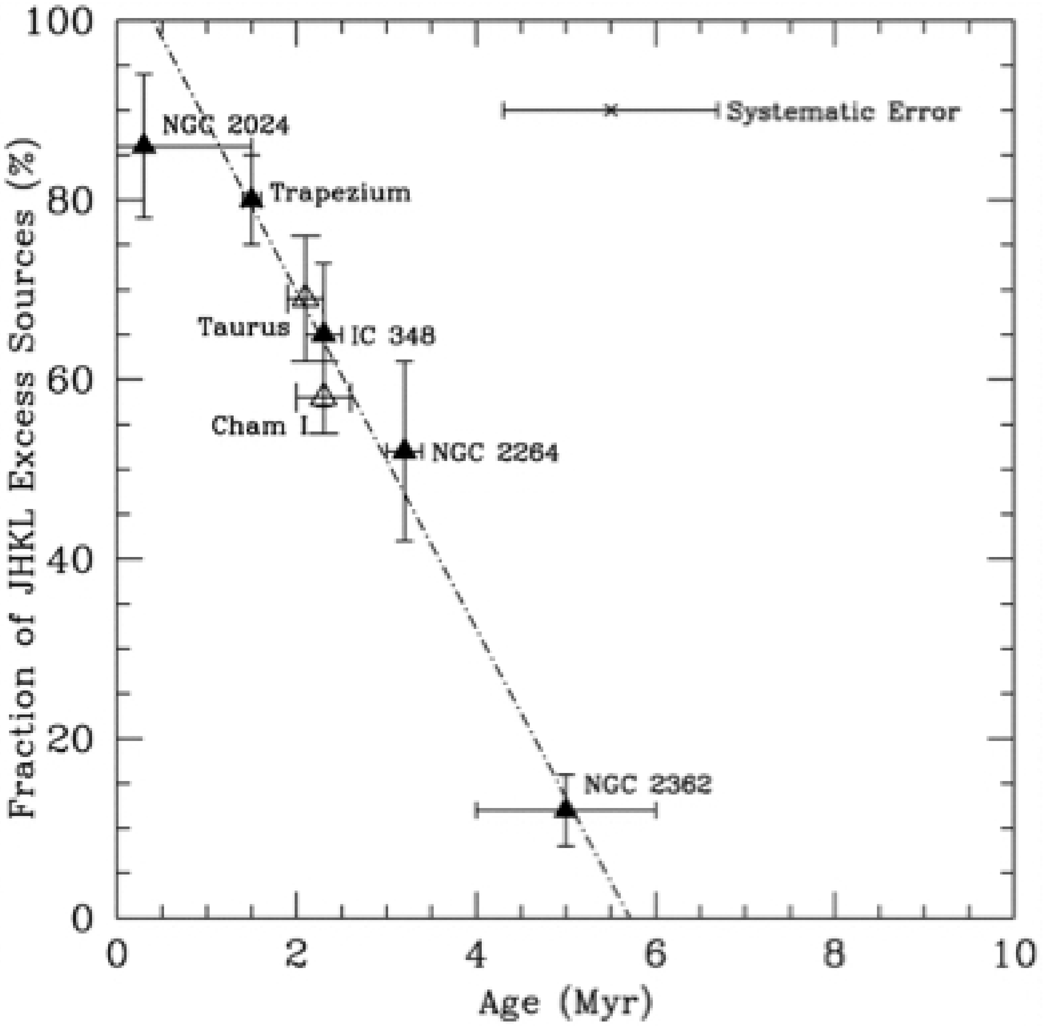

FIG. 6.— The decline in infrared excess, indicating warm dust in a disk, with age is rapid, meaning disks have a limited amount of time to assemble planets. Transition disks may be a significant fraction of the disk lifetime (Currie 2010), but evidence also suggests that planet formation can continue in the outer disk after the inner disk is depleted. ALMA can resolve the physical conditions in disks as a function of radius and assess the conditions for planet formation directly. (Haisch et al. 2001)

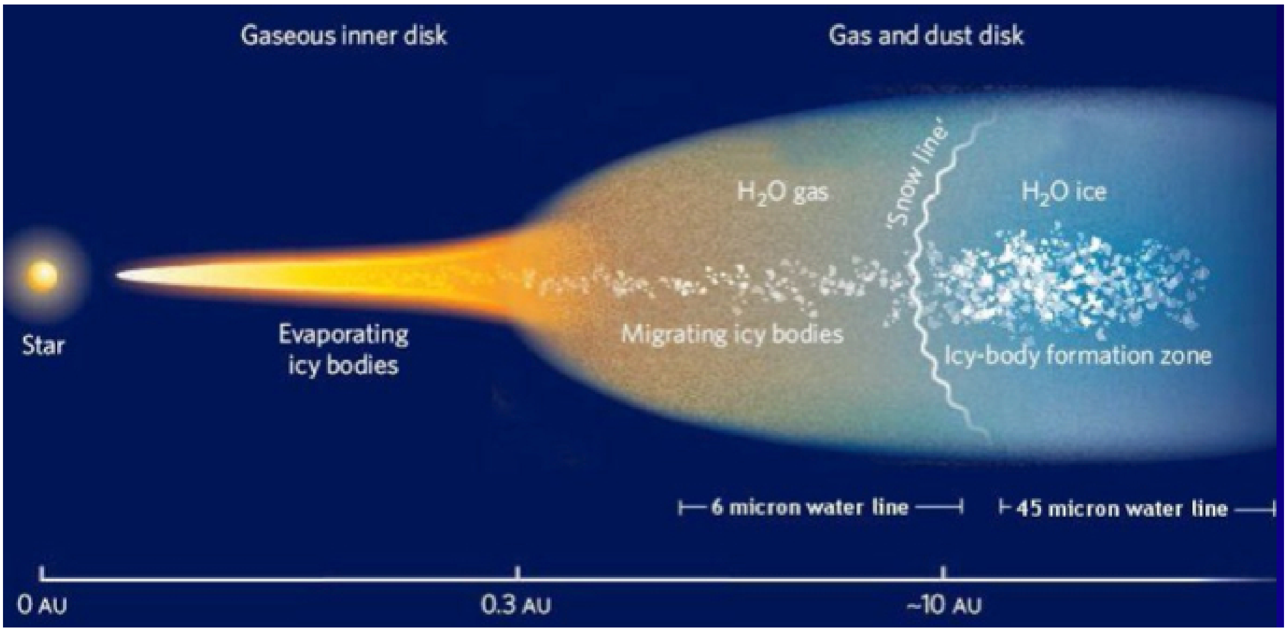

FIG. 7.— Cartoon showing the variation of transition disk structure and content by radius.

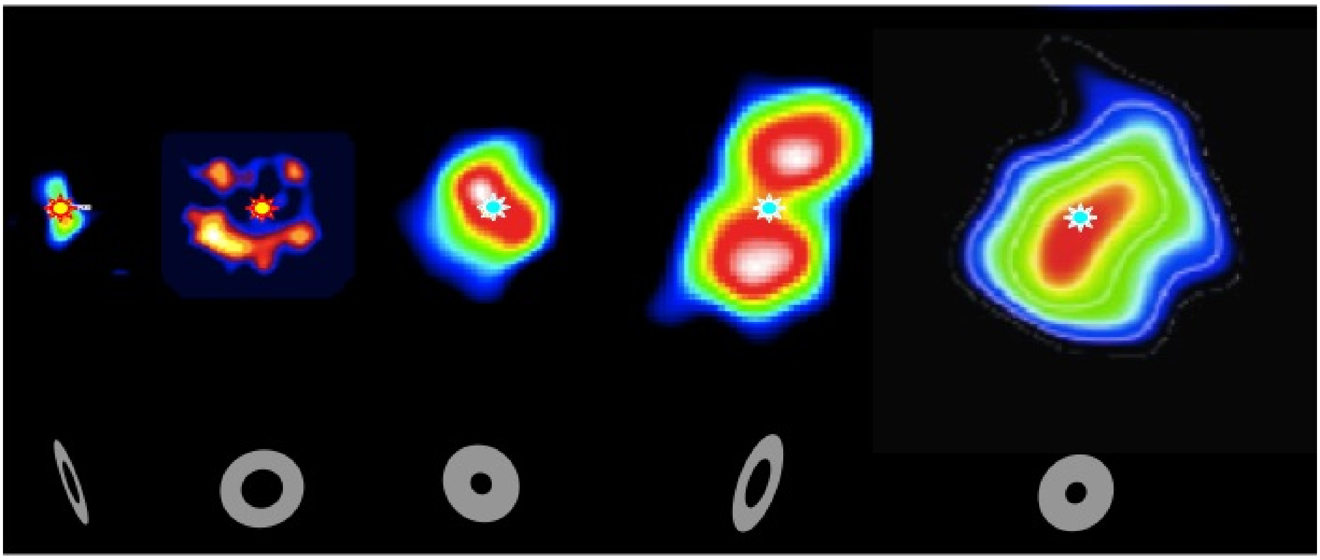

FIG. 8.— When SCUBA was commissioned in 1997, only one debris disk had been resolved at any wavelength (β Pic). At the time of its decommissioning in 2005, SCUBA had provided seven of the fourteen resolved images of debris disks, detecting spatially extended cold disk components unseen in scattered light and revealing asymmetries associated with orbiting planets (e.g., Vega, Wyatt 2003). From left to right are images of the disks τ Ceti, ϵ Eridani, Vega, Fomalhaut and η Corvi. The inferred disk orientations are shown below each SCUBA image, explaining some of the diversity observed.

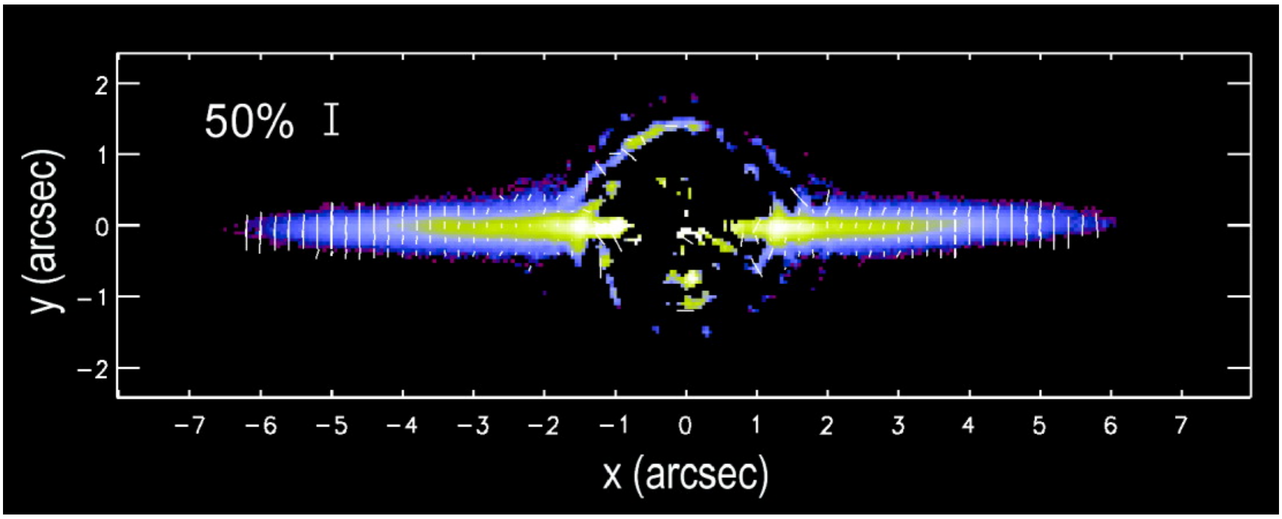

FIG. 9.— AU Mic scattered light image from HST with polarization vectors shown which suggest the dust in AU Mic's disk is highly porous (Graham, Kalas & Matthews 2007). AU Mic is now one of the most studied debris disks and is part of a Guaranteed Time Programme on the Herschel Space Observatory to resolve its structure and better characterize the physical properties of the dust in its disk (along with the disks of β Pic, Vega, τ Ceti, Fomalhaut and η Corvi). The Herschel team includes several Canadian researchers.

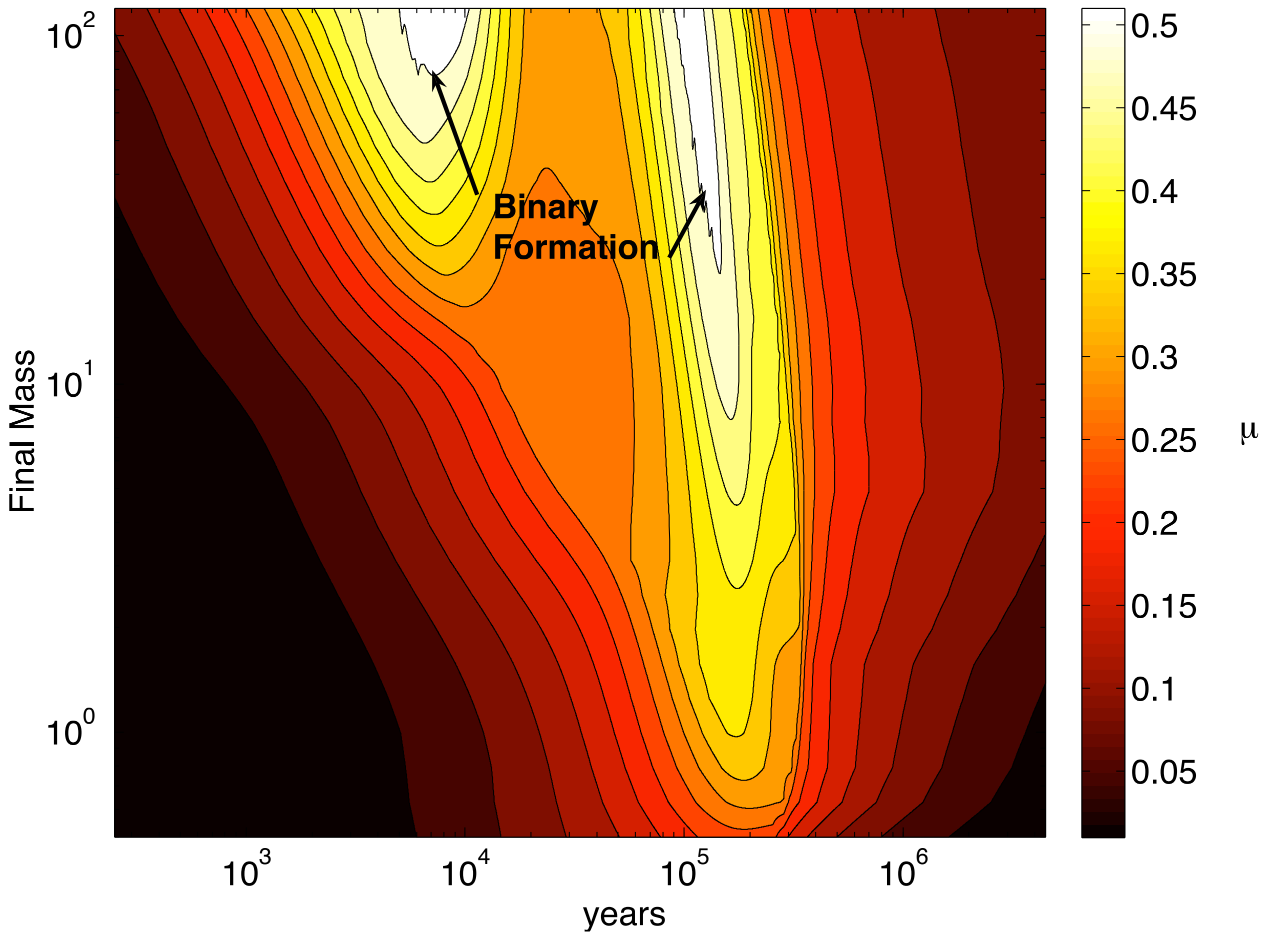

FIG. 10.— Prediction for the formation of binary stars due to gravitational disk instability in rapidly-accreting systems, across a wide range masses, from Kratter et al. (2008). Contours indicate the ratio of disk to total system mass within a one-zone model with detailed thermodynamics but simplified disk dynamics. Systems can be susceptible to binary formation in zero, one, or two epochs of their rapid accretion phase, depending on the system mass.

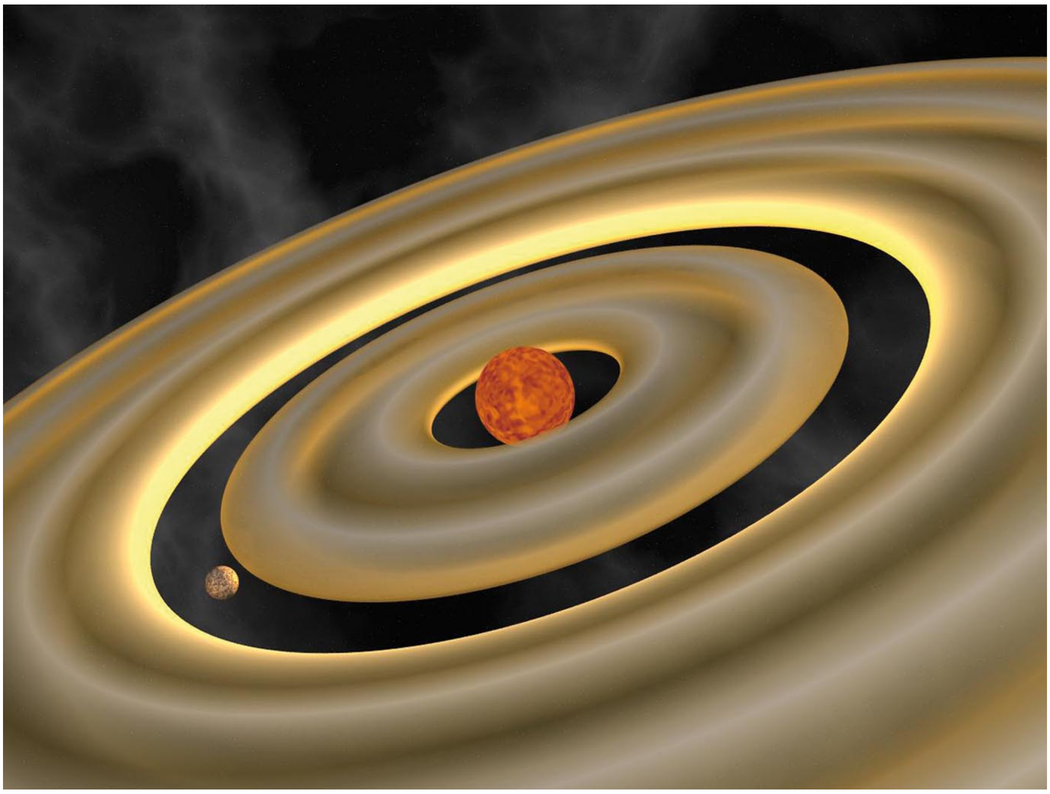

FIG. 11.— Model showing the clearance of a gap in a disk due to an orbiting planet.

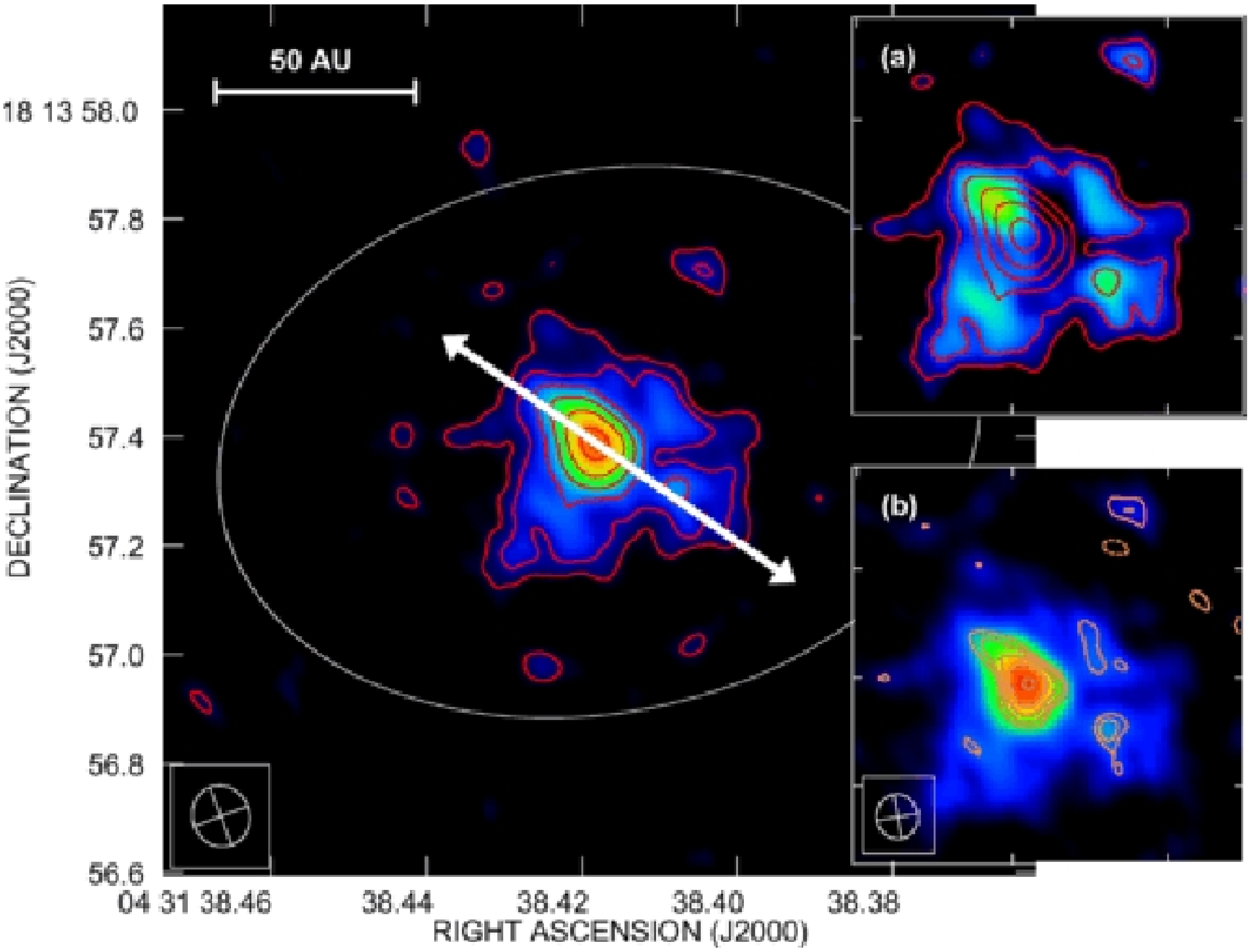

FIG. 12.— VLA 1.3 cm images towards HL Tau shows a condensation to the northwest of the main HL Tau disk. The jet direction is indicated by the white arrow. The ellipse shows the extent of the disk as measured at 2.7 mm with 0.6 arcsec resolution. The large image shows natural weighting of the data with a beam (lower left) of 0.11 arcsec. Contours are (4.0, 5.7, 8.0, 11.4, 16.0) ÃŮ17 μJy beam^{-1} (1σ). The upper inset shows the same data with a central peak of 263 μJy subtracted. This highlights the jet bases and two features at $\sim$20 AU at the ends of the disc major axis. Contours from the unsubtracted image are overlaid. The lower inset shows the uniform weighted data to achieve higher resolution of 0.08 arcsec, with contours at (3.0, 4.2, 6.0, 8.5, 12.0) ÃŮ21 μJy beam^{-1} (1σ), highlighting the compact object. (Greaves et al. 2008)

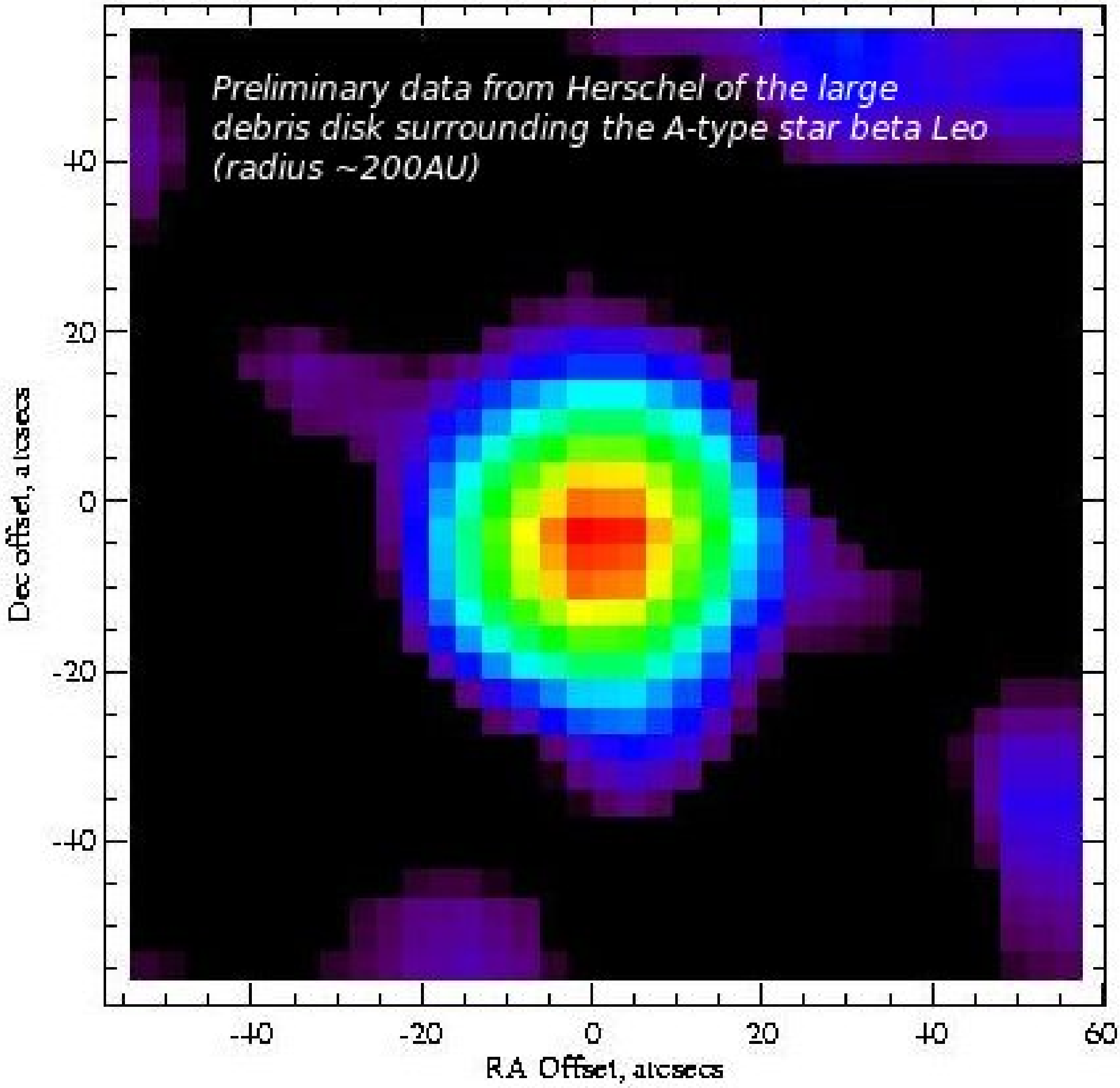

FIG. 13.— Spectacular early 110 μm image of the disk surrounding the star β Leo, taken during the Science Demonstration Phase with Herschel for the DEBRIS Key Programme (PI: Matthews). Preliminary estimates suggest that the disk is 400 AU across, although it was not resolved by Spitzer. This suggests that there are strongly emitting grains at 110 μm that were not detectable at 70 μm. The superlative resolution of Herschel (7$''$ at 110 μm versus 18$''$ at 70 μm with Spitzer) reveals significant variation across the disk. Of the six known disk hosts targeted during SDP, Herschel has resolved three which were previously unresolved. (Matthews et al. 2010, in preparation)

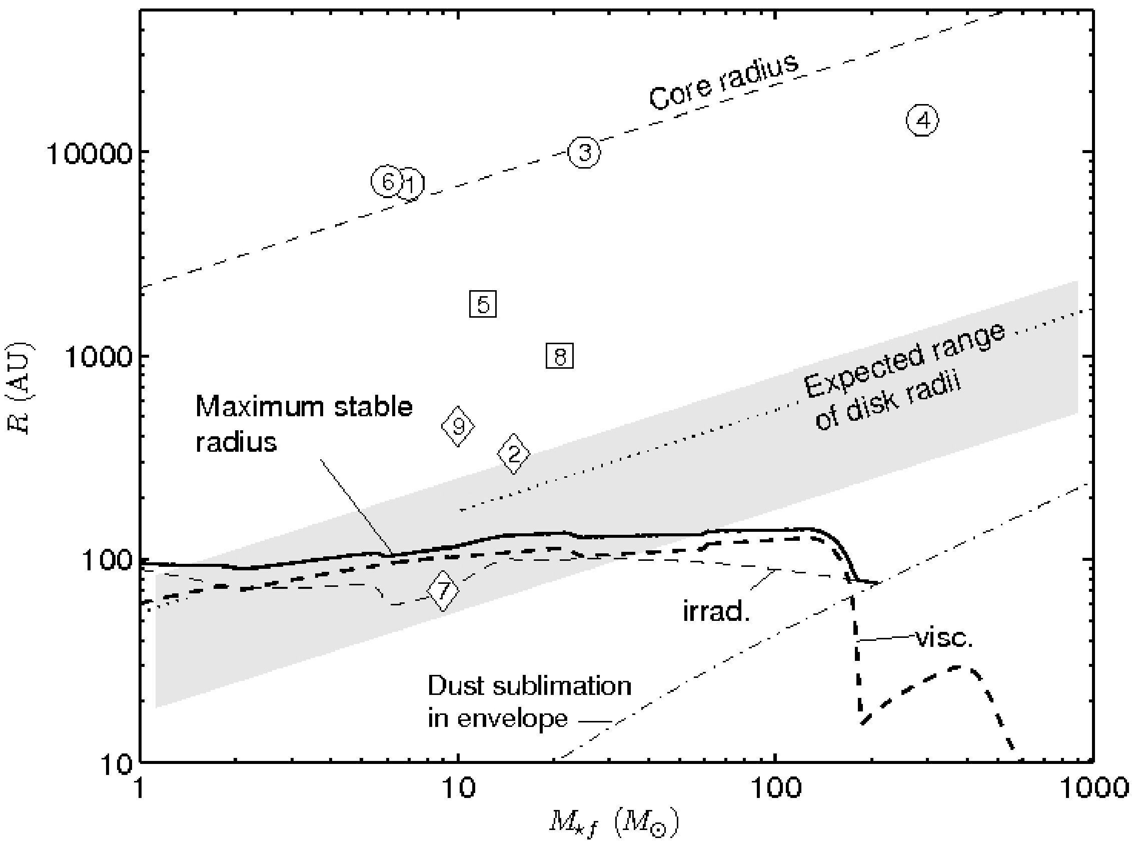

FIG. 14.— Prediction of disk fragmentation due to gravitational instability during massive star formation, from Kratter & Matzner (2006). Disk radii are modeled for a range of the final stellar mass and compared against the maximum stable radius (about 100 AU) and against a sequence of observed disks, tori, and rotating envelopes (diamonds, squares, and circles).